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BALANCED, PARALLEL OPERATION OF FLASHLAMPS*

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ABSTRACT

A new energy store, the Compensated Pulsed Alternator (CPA), promises to be a cost effective substitute for capacitors to drive flashlamps that pump large Nd:glass lasers. Because the CPA is large and discrete, it will be necessary that it drive many parallel flashlamp circuits, presenting a problem in equal current distribution. Current division to ± 20% between parallel flashlamps has been achieved, but this is marginal for laser pumping. A method is presented here that provides equal current sharing to about 1%, and it includes fused protection against short circuit faults. The method was tested with eight parallel circuits, including both open-circuit and short-circuit fault tests.

Introduction

The new Nova solid state laser will require an energy storage system of at least 100 MJ size to drive the 5 to 10 thousand flashlamps that will pump the glass. This type of distributed load is normally driven with an equally distributed energy store - namely a capacitor bank of many modules. Alternative stores to capacitors, such as the compensated pulsed alternator, are only practical in large single sizes, however, so the requirement exists to learn how to drive many parallel flashlamps.

Flashlamps are nonlinear resistive loads with a resistance that decreases as the current through them increases. Equal current sharing will therefore not necessarily be achieved when the lamps are operated in parallel. Inall[1] has demonstrated parallel operation of 16 flashlamp circuits with equal current sharing to within 20%, provided all lamps are properly preionized. In this paper, we report upon a simple method using inductors with reacting mutuals in each lamp circuit, that provides parallel current sharing within about one percent. The method requires no special preionization circuitry: lamp triggering is accomplished with the LC ringup between the inductor and the lamp cable capacitance.

Summary of Results

An experimental system was constructed in which eight parallel flashlamp circuits, were driven by a single 200 kJ, 20 kV capacitor bank. Each circuit comprised two series 44-inch long, 15-mm bore, xenon filled flashlamps, a fuse, and an inductor. With an inductance of 112 μH in each circuit, equal current division to about 4% was achieved. When inductors were stacked together so that the mutuals subtracted, they became balancing reactors. With this arrangement, current division within measurement error (∿ 1%) was achieved and the effective series inductance in each circuit dropped to about 15 μH.

Open circuit tests were also made. When one of the flashlamps was disconnected, the remaining seven circuits shared the full bank energy, and balancing was achieved as before.

The worst-case unbalance occurs when a flashlamp breaks and the circuit becomes shorted. This case was simulated with a deliberate short in place of the lamp. With a 112 μH inductor in each circuit, the currents in the seven normal circuits balanced well, but the current in the shorted circuit rose at three times the nominal value until the fuse

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A new energy store, the Compensated Pulsed Alternator (CPA), promises to be a cost effective substitute for capacitors to drive flashlamps that pump large Nd:glass lasers. Because the CPA is large and discrete, it will be necessary that it drive many parallel flashlamp circuits, presenting a problem in equal current distribution. Current division to t 20% between parallel flashlamps has been achieved, ~ut this is marginal for laser pumping. A method is presented here that provides equal current sharing to about 1%, and.it includes fused protection against short circuit faults. The method was tested with eight parallel circuits, including both open-circuit and short-circuit fault tests.

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burst. The energy dissipated by the fused shorted circuit was about 1.5 to 3 times the normal value depending on the fuse size.

Parallel flashlamp operation has therefore been demonstrated. Series inductances work well but balancing reactors provide the most uniform current sharing. If a flashlamp fails to fire, the remaining lamps share its energy. In a laser amplifier this would be advantageous, since the pumping efficiency would then remain virtually unchanged. A shorted circuit can be protected adequately with a fuse. It will reduce the energy delivered to the other lamps by up to three times its normal share. In a large system, however, this amount of energy loss would be insignificant.

Test Configuration

The test circuit schematic is shown in Fig. 1. Each of the eight circuits comprised eight parallel 14.5 μF capacitors; however, all eight circuits were connected together at the charge resistors (Point A in Fig. 1) as shown, effectively forming a single 928 μF capacitor bank.

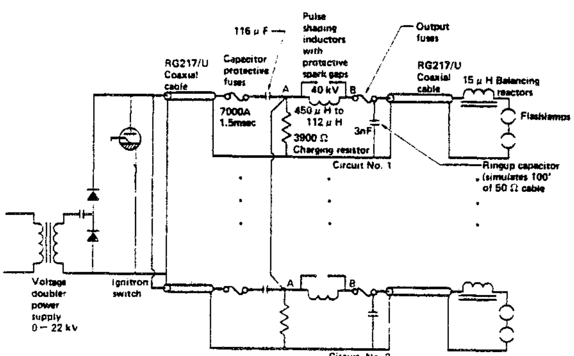


Fig. 1: Test Circuit Schematic

During the experiment, the pulse shaping inductors were varied from 450 μH to 112 μH. For the final phase of testing, these inductors were placed in parallel by additionally connecting the eight circuits together between the inductors and output fuses (Point B in Fig. 1). For this case balancing reactors of 15 μH were inserted directly at the flashlamps. The sparkgaps protecting the inductors were set at 40 kV. The fuses protecting the capacitors were 700 A/1.5 msec and the output fuses were 5000 A/1.5 msec or 7000 A/1.5 msec depending upon the test performed.

Circuit performance was monitored by measuring currents via four Pearson #301X probes and recording these waveforms on a Tektronix 5441 oscilloscope with a four channel input. These current probes are useable to 50 kA. Photographs of scope traces were taken to preserve the data.

Procedure

The first test demonstrating parallel operation used a 450 μH pulse shaping inductor in each circuit. The inductor's value was halved twice: first to 225 and then to 112 μH. For each inductor value a number of shots were taken at voltages ranging from 16 to 22 kV. In order to view all eight flashlamp currents on a single shot, two circuits were strung through each Pearson probe. Then each waveform was the sum of two currents.

Special cases of one circuit open and one circuit shorted were investigated. To simulate a shorted flashlamp circuit, one series pair of lamps was replaced by a hard wire short. Open circuits were simulated by opening one circuit at point "B", Fig. 1. Open circuit tests were performed with 112 μH inductors, and with intial charge voltages of 16 to 18 kV. Short circuit tests were performed with two sizes of output fuses (5000 A and 7000 A) and with 112 μH inductors at an initial capacitor charge voltage of 16 kV. A short circuit test was also performed at 20 kV with a 5000 A fuse output and 112 μH inductors.

The pulse shaping inductors were then connected together by paralleling the circuits at point B, Fig. 1. The test circuit then comprised one large capacitor (928 μF), one inductor (14 μH), and eight parallel flashlamp circuits. Balancing reactors were used in each flashlamp circuit. These were nominally 44 μH pancake inductors that were stacked together in alternate fashion so that adjacent mutuals subtracted. Two of these

inductors were paralleled for each circuit. The resulting series inductance in each circuit was 15 μH. Normal operation and one circuit open tests were run. A short circuit test was not possible due to current limitations on the balancing reactors.

Test Results

Selected current waveforms from tests that used series inductors for current balancing are given in Fig. 2. Short circuit test waveforms are given in Fig. 3, and waveforms of tests using balancing reactors are given in Fig. 4.

Current Balancing via Series Inductors

Tests with 450 μH, 225 μH, and 112 μH series inductors in each of the eight flashlamp circuits demonstrated a maximum current imbalance of about 4%. The case with the greatest imbalance (112 μH) is presented in Fig. 2. Figures 2a and b each show four traces with two circuits per trace, and normal operation (no opens or shorts). In Fig. 2a the capacitors are charged to 16 kV, giving 120 kJ for the 8 circuits. Figure 2b is with 22 kV charge and 225 kJ total.

Figure 2c is 16 kV (120 kJ) and one circuit open. Three of the traces have two live circuits each, showing good balancing. The single trace with only one live circuit shows just half the current of the others. Thus the current divides properly in all seven active circuits. Analysis shows that the average energy dissipated by each circuit is just 8/7 of that dissipated by the normal case when all eight circuits are active (Fig. 2a).

Short Circuit Tests

Figures 3a and b are short circuit tests at 16 kV charge and with 112 μH balancing inductors. In each picture, three circuits are strung through each of two of the Pearson probes. A single normal circuit is strung through the third probe and the shorted circuit through the fourth. In each case, analysis shows that all seven normal circuits balance well (within a few %). The shorted circuit, however, draws about three times the current of the other circuits until the fuse blows. The 7000 A/1.5 msec fuse (Fig. 3a) blows at 22 kA, and the 5000 A/1.5 msec fuse (Fig. 3b) blows at 15 kA.

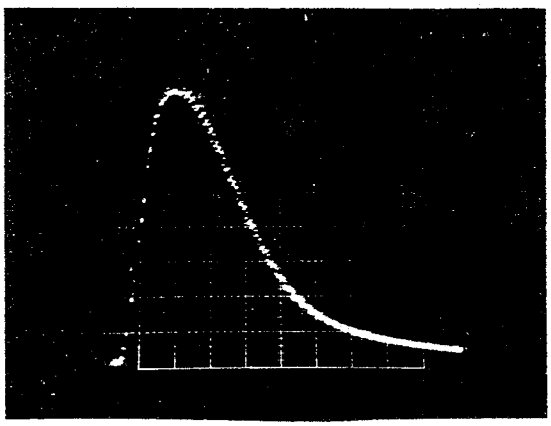
In the first case, the energy dissipated by the shorted circuit was about 40 kJ instead of the normal 15 kJ. In the second case, with the smaller fuse, about 29 kJ instead of 15 kJ were dissipated by the short. A third short circuit test (not illustrated) was made with the smaller fuse, and with the bank charged to 20 kV (190 kJ). In this case, the fuse blew at 17 kA and the shorted circuit dissipated 34 kJ, instead of the normal 24 kJ.

Note that the energy dissipated by a shorted circuit would be a very small fraction of the energy in a large parallel lamp system. Since the fuse limits the energy dissipated by the short, regardless of system size, no significant degredation of laser system performance is anticipated because of a shorted circuit.

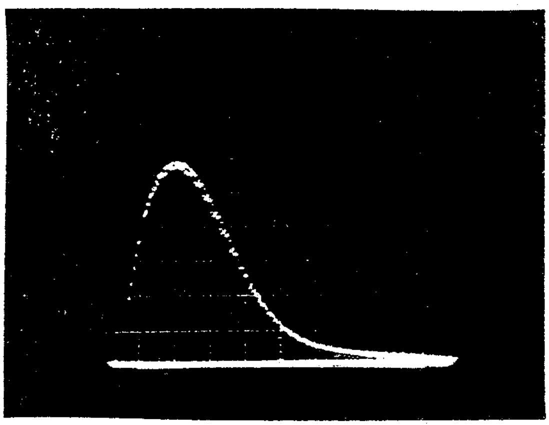
Current Balancing via Balancing Reactors

The results for current sharing tests using balancing reactors is given in Fig. 4a. Four traces are shown (two circuits per trace), and the bank is charged to 16 kV. Since the traces lie one on top of the other, with no separation, we surmise that current balancing is achieved within measurement error (∿ 1%).

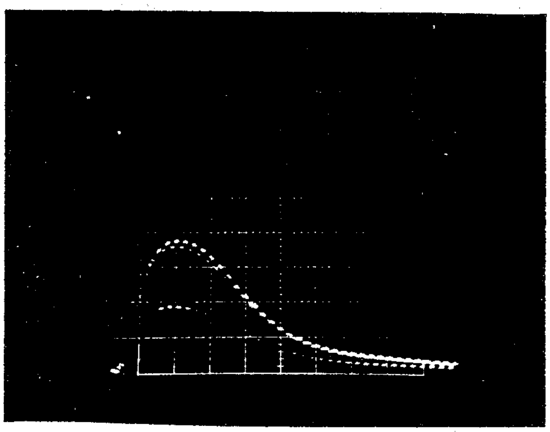
An open circuit test is presented in Fig. 4b. Here the seven normal circuits balance within measurement error, and they share equally all of the circuit energy.



a. 15 kV charge, 1000 A/div, 100 μsec/div

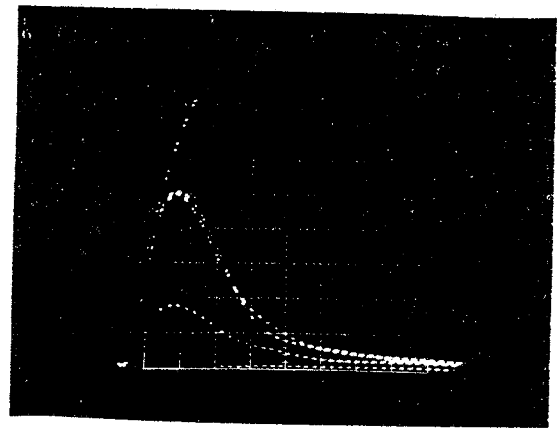


b. 22 kV charge, 2500 A/div, 100 μsec/div

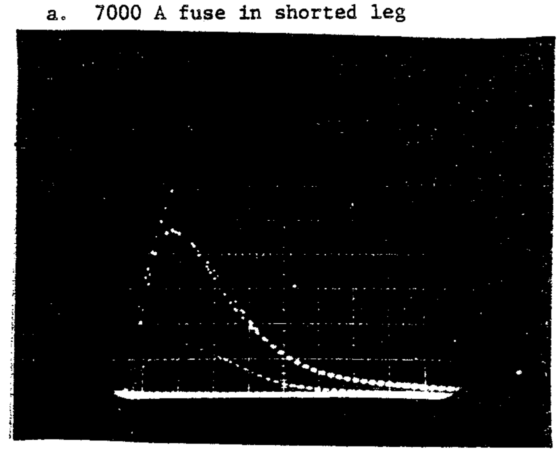


c. 16 kV charge, 2500 A/div, 100 μsec/div
one circuit open

Fig. 2: (a,b,c) Eight-circuit parallel flashlamp test using 112 μH inductors in each circuit

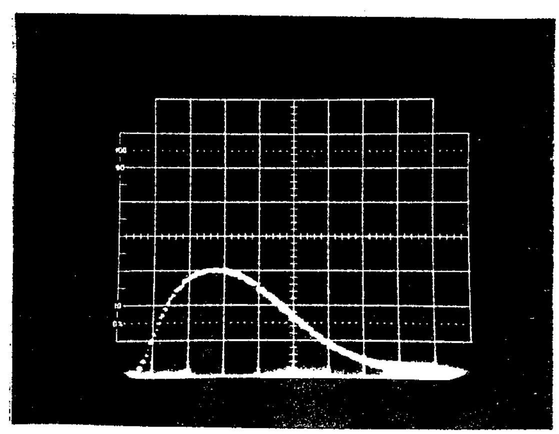


a. 7000 A fuse in shorted leg

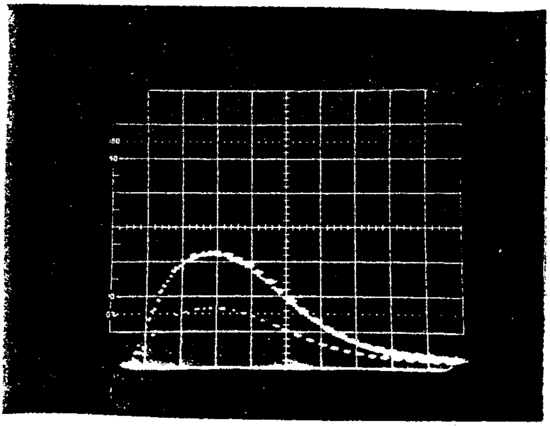


b. 5000 A fuse in shorted leg
2500 A/div, 100 μsec/div

Fig. 3: (a,b) Short circuit test. 112 μH inductors in each of 8 parallel flashlamp circuits, with two fuse sizes in shorted circuit.



a. Eight normal circuits



b. One circuit open
16 kV charge, 2500 A/div, 100 μsec/div

Fig. 4: (a,b) Eight-circuit parallel flashlamp tests using current balancing reactors with effective 15 μH inductance in each circuit.

Reference

1. E.K. Inall "Powering Laser Flashlamps from a Storage Inductor", High Power High Energy Pulse Production and Application, ANU Press, Canberra, Australia, 1978.

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